MCR-76-3

Volume I

Executive Summary

March 1976

Space Tug Docking Study

(NASA-CR-144239) SPACE TUG DOCKING STUDY. VOLUME 1: EXECUTIVE SUMMARY Final Report (Martin Marietta Corp.) 49 p HC $4.00 CSCL 22B G3/16

N76-21245

Unclas

25162

MARTIN MARIETTA

MCR-76-3
Contract NAS8-31542
Data Procurement Document No. 510
Data Requirement No. MA-04

Volume I

Executive
Summary

March 1976

SPACE TUG DOCKING STUDY

Approved By

G. J. Dickman

G. J. Dickman
Program Manager

MARTIN MARIETTA CORPORATION
P. O. Box 179
Denver, Colorado 80201

FOREWORD

This study was performed under Contract NAS8-31542 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration under the direction of Mr. James I. Newcomb and Mr. Paul T. Craighead, the Contracting Officer's Representatives. The final report consists of five volumes:

- Volume I - Executive Summary
- Volume II - Study of Results
- Volume III - Procedures and Plans
- Volume IV - Supporting Analyses
- Volume V - Cost Analysis

The study results were developed during the period from June 1975 to January 1976. Principal Martin Marietta contributors to the study were:

Glen Dickman	Study Manager
G. Dickman	Task A Leader, Requirements and Data Base Development
B. King	System Requirements and Operations Analyses
R. Zermuehlen	Subsystem Requirements
R. Schappell	Video Sensors
W. Koppl	Ranging Sensors
C. Park	Docking Dynamics Analysis
B. Dickman	Docking Simulation Program
F. Vandenberg	Rendezvous Simulation Program
M. Crissey, J. Hays, C. Lord	Docking Mechanics
R. Chamberlain	Payload Requirements
R. Zermuehlen	Task B Leader, Candidate System Definition
B. King	Task C Leader, Simulation Demonstration Test Program Definition
E. Cody	Task D Leader, Programmatics Definition

CONTENTS

Table

I. INTRODUCTION

Rendezvous and docking is the key operational technology of the space transportation system (STS) era--the 1980's and 1990's. Studies are being conducted now regarding the development of a fleet of manned and automated spacecraft which would be deployed and maintained in this time frame. Permanent manned space stations to be assembled and utilized are being studied. Spacecraft retrieval and/or servicing, orbital assembly, and manned crew rotation all require rendezvous and docking. As the objectives of space flight become more complex, rendezvous and docking operations will be more frequently used. These operations may be under direct manned control as in the case of Shuttle--or a manned orbital transport vehicle (OTV). They may be under remote manned control or autonomous operations in the case of an unmanned OTV or space tug. Direct manned rendezvous has been operational since Gemini, but remote manned and autonomous rendezvous is a new technology for the United States.

This space tug docking study was commissioned by the Marshall Space Flight Center in response to the anticipated increased requirements for rendezvous and docking. It particularly addresses the question of remote operation--either with remote manual control, autonomous control, or some best-mix hybrid approach. This particular study compiled a data base of technology relating to components and techniques, configured and compared functional systems, and recommended the simulation/demonstration programs required to develop a remote rendezvous and docking capability.

A two-step requirements analysis was conducted. Systems level requirements were derived largely from a search of related documentation to establish the basic definition of what the docking system must accomplish. A wide variety of requirements were found, but two key elements stand out. The long range navigation problem can be essentially solved by the Tug navigation system. The docking mechanism must be compatible with the support of up to three spacecraft in the Shuttle flight environment, and must provide a capability to deliver one diameter payload and retrieve another. These requirements have particularly significant impact on subsystem requirements.

The approach to subsystem requirements was largely analytical, relying on digital simulation programs for rendezvous maneuvers, docking maneuvers, and docking dynamics--supplemented by sensitivity studies and basic engineering analyses. Complete subsystem level requirements were developed. Among the most interesting results were that rendezvous sensor accuracy, in this operational setting, is not a driving design requirement. Rather, the ability to measure lateral velocity and line of sight relative to the docking port during final closure become driving issues. Further, it was found that the propellant slosh problem is not a significant contribution to docking mechanism design loads, though it is a significant consideration for post-docking attitude control.

A careful review of components capable of meeting subsystem requirements revealed that laser and RF radars can be used singly or in combination with TV systems to meet manual and autonomous subsystem requirements. The most attractive docking mechanisms are derived from the Apollo probe/drogue approach, application of the MDAC square frame, or a new hybrid soft dock approach based on the application of a controllable, extendable probe for actual docking contact.

Several systems were configured from the basic components, all of which were capable of meeting system level requirements. They were ranked using a numerical approach applied to a carefully selected set of cost, performance, and growth potential criteria. The intent of this ranking was to find the most promising approaches for further design concentration in subsequent efforts. This study has found that remote rendezvous and docking under manual control is readily accomplished by current technology. Conventional RF radar and TV systems can be combined to effect manually controlled docking with conventional docking mechanisms. Autonomous docking requires some modest new development in sensor technology. Either scanning laser radar (SLR), close-range RF docking radar, or autonomous TV docking algorithms must be developed and flight qualified. These developments are very reasonable outgrowths of current technology and represent an acceptable level of development risk. A hybrid approach to remote rendezvous and docking seems especially attractive. From a developmental point of view, it provides a risk-free evolution to an autonomous docking capability. Manned supervision/intervention can be used on developmental flights until

confidence is gained in autonomous techniques. It also provides the flexibility needed to cope with unforeseen events that fall outside the preprogrammed capability of an operational autonomous system.

These most promising approaches to rendezvous and docking system development formed the basis for definition of SRT activity and a simulation/demonstration program. The intent of these activities is to provide data on which to base a sound selection of a proven rendezvous and docking design approach. Key simulation/demonstration tests required to meet this objective were defined in the areas of rendezvous, inspection, docking closure and docking contact. Detailed test procedures were developed, and the associated facility modification, test preparation, and test conduct efforts estimated. This planning activity provided a sound basis for recommendation of further development effort in the areas of SRT, laboratory testing, and rendezvous and docking system integration.

II. STUDY OBJECTIVES

The overall objective of this study was to provide a detailed system analysis of the entire rendezvous and docking operation to be performed by the all-up space tug. This objective was divided into three specific areas--generation of requirements and a data base of candidate operational techniques and subsystem mechanizations, selection and ranking of integrated system designs capable of meeting the requirements generated, and definition of the simulation/demonstration program required to select and prove the most effective manual, autonomous, and hybrid rendezvous and docking systems. These objectives have been supported by programmatic analyses to assure cost-effective schedule-conscious selections and recommendations.

Much of this activity has been addressed in previous studies conducted for MSFC, particularly in the areas of initial rendezvous (Tug Avionics Study/General Dynamics), payload support requirements (Payload Requirements Study/McDonnell Douglas), and servicing (Orbital Servicing Study/Martin Marietta). The objective of this study was to build on the results of these previous studies and concentrate on the final phases of inspection, alignment, closure, and docking. The results of this study can affect previous decisions in the earlier phases of rendezvous and are affected by considerations of spacecraft structural support, operational autonomy level, spacecraft cooperation, and servicing objectives. These considerations were factored into the decisions and selections made during this study.

The objective of the requirements and data base activity was twofold--to analyze operational objectives and interfacing systems to derive the functional requirements to be imposed on the rendezvous and docking system, and to review existing, and conceptualize new, components, operational strategies, and specific mechanizations for meeting the functional requirements developed. The data base includes the data required to conduct budget tradeoff, evaluate cost and development risk, and generally support system selection and ranking. This activity particularly included the flight mechanic and structural dynamic analyses required to evaluate the effects of the maneuver and docking options under consideration.

The objective of the candidate system definition activity was to synthesize system designs capable of meeting operational requirements and then to rank these systems relative to their overall desirability. The candidate systems generated include those that require real-time ground support with manual control, systems capable of autonomous operation, and hybrid approaches combining the best features of the manual and autonomous systems. Cost consciousness was a particularly significant criterion in the selection process, and one system was selected with development cost as a primary consideration. Analyses proving requirements compatibility and the rationale for ranking candidates were considered an important output of this activity.

The objective of the simulation/demonstration activity was to develop a plan for laboratory testing of promising rendezvous and docking concepts that will lead to evolution of the most desirable operational system. Test requirements were derived from analysis of the critical functions associated with the most promising systems synthesized in the candidate system selection task. The output included a logic flow showing recommended steps from problem to solution and a time-phased flow of inputs and outputs of the simulation/demonstration subtasks depicting their relationship to each other and to tug program milestones. The test planning process included mating test procedures with existing/modified facilities at MSFC. Another study objective was to identify any new test facilities required to meet simulation/demonstration goals.

Programmatic analyses were required to support the data base, system selection, and simulation/demonstration objectives delineated. The analyses in support of the data base development addressed development cost and cost/schedule risk parameters. Support of system selection required emphasis on low development cost in addition to the parameters of performance, reliability, weight, and operational complexity. The simulation/demonstration programmatic support concentrated on the costs associated with software, test equipment, facilities, and manpower. The overall programmatic objective was to assure that each decision in the selection and development of a rendezvous and docking system was made with an awareness of its impact on cost effectiveness.

The particular objective of this study has been tied to the fully capable space tug vehicle. The technology covered is, however, applicable to any of the wide variety of rendezvous and docking activities anticipated during the STS era of space exploitation. In meeting space tug objectives, a large step has been made toward meeting most future rendezvous and docking objectives.

III. RELATIONSHIP TO OTHER NASA EFFORTS

This space tug docking study (STDS) benefitted considerably from previous related studies and from previously developed technologies. The thrust of this study was toward remote docking--either ground controlled or autonomous. Past manned rendezvous technology is applicable in the area of rendezvous sensors and docking mechanisms. More recent study efforts have concentrated on the rendezvous phases, permitting this study to concentrate on docking and only reflect back the implications of what was learned on the earlier phases. Efforts conducted in the area of spacecraft support requirements have also been beneficial. A summation of source material is presented in Table III-1 and Table III-2.

Table III-1 Closely Related Study Efforts

- Baseline Space Tug System Definitions
  Marshall Space Flight Center, 1974
- Space Tug Avionics Definition Study
  General Dynamics/Convair Division, 1975
- IUS/Tug Payload Requirements Compatibility Study
  McDonnell Douglas Astronautics Company, 1974
- Payload Utilization of Tug - Follow-On
  McDonnell Douglas Astronautics Company, 1974
- Integrated Orbital Servicing Study for Low-Cost Payload Programs
  Martin Marietta Corporation, 1975
- Earth-Orbital Teleoperator System Concepts and Analyses
  Martin Marietta Corporation, 1975
- Multiuse Mission Support Equipment (MMSE)
  Martin Marietta Corporation, 1975
- Automated Payload Definition and Requirements Data (SSPD)
  Marshall Space Flight Center, 1974
- Space Tug Automatic Docking Control Study, Lockheed Missiles & Space Company, 1974

Table III-2 Prior System and Subsystem Developments

- Docking System Development
  - Flight-Proven Hardware
    - Apollo Probe/Drogue
    - Gemini Ring/Cone
    - ASTP Androgenous
  - Advanced Concept Developments
    - Square Frame (MDAC)
    - Pivoting Arm Servicer (TRW)
    - Apollo Candidate Developments
- Sensor System Development
  - Flight-Proven Hardware
    - Apollo/LEM RF radar
    -
  - Advanced Concept Developments
    - GaAs Scanning Laser Radar (MSFC/ITT)
    - CO_2 Scanning Laser Radar (MSFC/Norden)
    - Shuttle RF Rendezvous Radar
    - Shuttle TV Camera

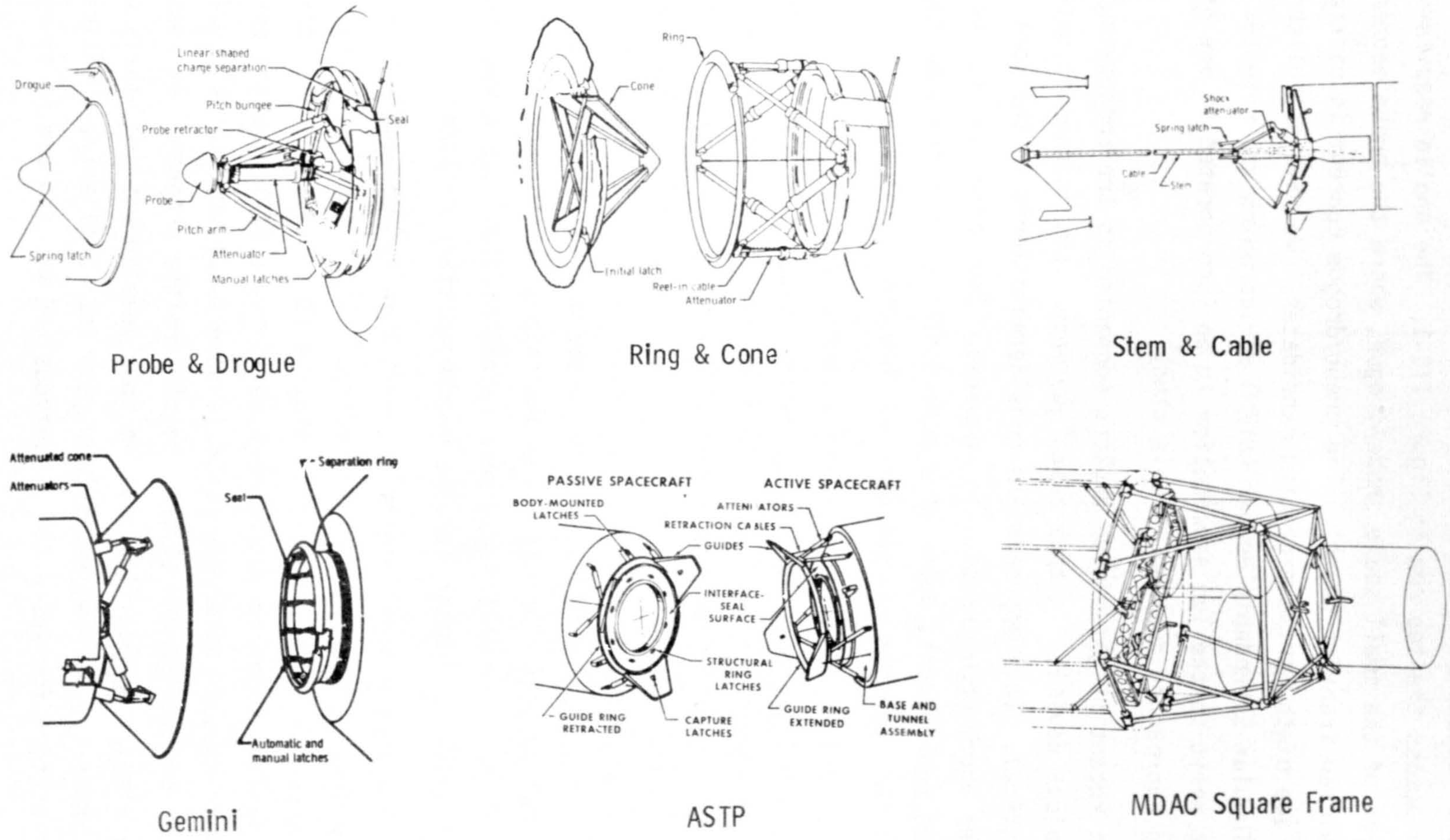
The General Dynamics baseline tug avionics study has been particularly important. The current study has presumed that the space tug will have the navigational accuracy of the baseline system recommended by General Dynamics. Due to the high quality of the interferometer landmark tracker (ILT) navigational updates used in the baseline tug navigation system, the scope of the problem to be solved by the rendezvous and docking system is considerably reduced. The navigational accuracy of this baseline system permits positioning the tug within 5.6 km (3 nautical miles) of its target. This reduces the requirement for rendezvous acquisition range to approximately 23 km (12.5 nautical miles) and leads to a safe acquisition sensor range specification of 46 km (25 nautical miles).

Payload information for this study has been gleaned from two principal sources--the automated payload definition and requirements data (the SSPD data sheets) issued by MSFC that do not generally reflect designs for reusability, and information relative to reusability obtained from the McDonnell Douglas payload utilization of tug effort. In particular, the retrievable versions of CSCSAT, SEOS, and COMR&DSAT from this study were investigated.* Two of these, CSCSAT (a CN-52 derivative) and SEOS (an EO-09 derivative), were selected as reference spacecraft for this study.

The means of supporting a spacecraft on tug in the shuttle flight environment is a key issue. The development of the preferred approach has been built on the docking experience generated by NASA in the decade since Gemini first docked with the Agena target vehicle. Figure III-1 illustrates the nature of this experience. The first operational docking mechanism used on the Gemini employed a large scale probe/drogue approach. This demonstration system was not driven by the more complex operational objectives that were to beset the Apollo system--and as a consequence was heavier and more unwieldy than the next generation of docking mechanism design.

---

* SEOS - Synchronous Earth Observation Satellite
COMR&DSAT - Communications R&D Satellite
CSCSAT - Commercial Synchronous Communications Satellite



MARTIN MARIETTA

Figure III-1 Existing Docking Concepts

The Apollo development process evaluated a variety of candidate approaches, as illustrated across the top row in Figure III-1. The Apollo requirements lea to the selection of the small scale probe/drogue, where the probe mechanism was mounted in the crew transfer tunnel. The probe/drogue concept is carried on in this study as one of the prime mechanism candidates. We have established that the Storable Tubular Extendable Member (STEM) device which was rejected for Apollo has sufficient merit in the Tug application to be incorporated in one of the candidate docking approaches pursued in this study.

The most recent flight proven docking mechanism is the androgynous Apollo/Soyuz test project device. In this case, the mechanisms mounted on both spacecraft are identical. This approach has considerable merit in the docking of two manned vehicles where crew transfer is required. The weight penalty associated with the manned requirements does not appear justifiable in the unmanned tug application, and this concept was not carried throughout this study.

Two recent NASA studies have provided further docking mechanism background data. McDonnell Douglas has been advancing the state of development for a square frame docking mechanism for some time. The version of this development considered in this study was derived from the McDonnell Douglas IUS/Tug payload requirements compatibility study. Application of the Apollo probe/drogue to Tug operations was investigated as a part of our multiuse mission support equipment study (NAS8-30847). This study recommended use of the probe/drogue with a standardized array of structural support elements. The operational experience from Gemini, Apollo, and ASTP combined with these more recent studies have given this space tug docking study a sound basis for the recommendations evolved.

Recent NASA sensor developments are particularly applicable to the tug rendezvous and docking problem. Laser radar development sponsored by MSFC, both gallium arsenide (GaAs) and carbon dioxide (CO_2) devices, are attractive candidates providing superior measurement performance at low weight and power. The Apollo/lunar module rendezvous radar is soon to be updated to operate in a noncooperative mode in support of the Shuttle orbiter program. As best understood at this time, the specifications on this development are nearly compatible with the space tug docking study requirements. Similarly, a silicon vidicon camera attractive for space tug rendezvous and docking use is expected to

be developed for Shuttle. These developments were taken into account in the definition and selection of recommended rendezvous and docking designs.

The earth-orbital teleoperator system (EOTS) concept study and the integrated orbital servicing study were conducted by Martin Marietta concurrently with the space tug docking study. A considerable sharing of ideas and personnel has improved the overall effectiveness of all three of these efforts. Particular areas of common interest and shared effort have been in the development of requirements and in the evaluation of docking mechanisms.

Perhaps the most significant relationships with other NASA efforts are yet to be developed. Rendezvous and docking operations will become more frequent in the coming years. They will be performed by both shuttles and orbital transport vehicles, and with a wide variety of operational spacecraft. It will be wise to make this technology development according to one integrated plan rather than several independent approaches. Money can be saved and a greater operational reliability/effectiveness can be achieved if an overview is taken of all requirements and a thoughful development process is implemented.

IV. STUDY APPROACH

The space transportation system is predicated on the economic benefits of reusability. Current mission models identify both up and down traffic--or delivery and retrieval of spacecraft. In this scenario a rendezvous and docking system capability has been assumed. The purpose of this study was to identify the areas of activity necessary to develop the rendezvous and docking capability in a timely manner. Study ground rules required the development of an autonomous system, a manual system, a hybrid "best-mix" system, and a low development cost system. The study was broken into the four major tasks shown in Figure IV-1.

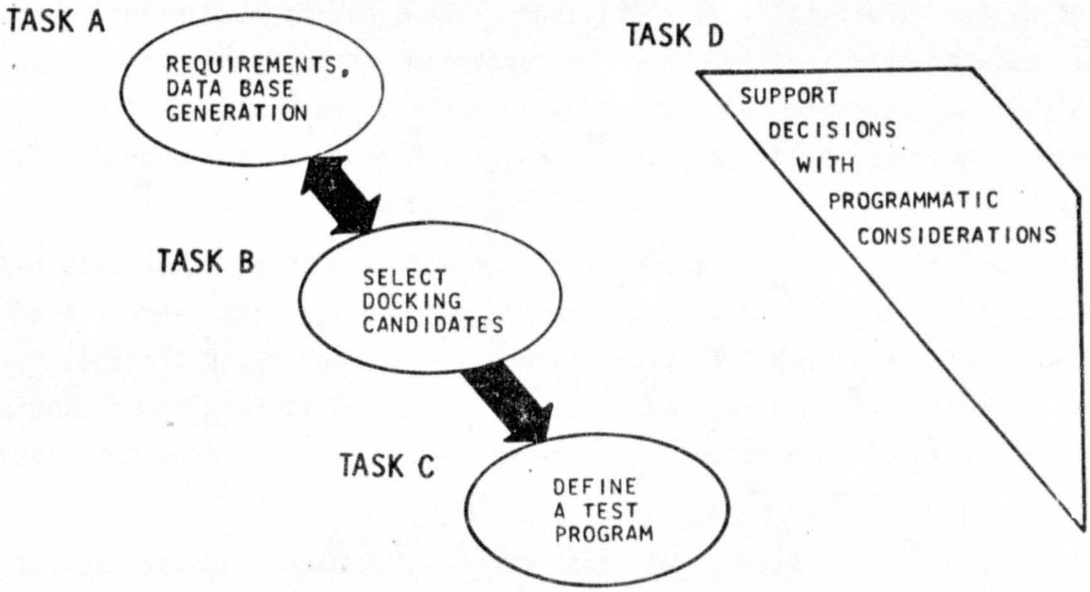


Figure IV-1 Study Tasks for System Development

The first task in the development of a rendezvous and docking capability was to derive the requirements that would be imposed on the system. Concurrently, a data base of candidate subsystem characteristics was generated. Subsystems were categorized into sensors, mechanisms, and strategies (algorithms). The requirements gleaned from existing sources were budgeted between the subsystems. Sources from which requirements were derived included space tug,

spacecraft, interfaces (orbiter-to-payload and tug-to-spacecraft), and mission operations documentation. Four representative spacecraft were selected for the study to cover the range of requirements, including weight, length, control systems, and orbital variations (inclination and altitude). Constraints on the system were utilized to bound the variables. The system-level requirements derived in this manner were budgeted to the subsystems and tradeoffs conducted.

The derived system-level requirements and the approach to subsystem budgeting were reported at a requirements briefing at MSFC in September 1975. Subsystem budgeting and candidate system definition tasks were followed.

Since the error contribution of the strategies can be made negligible by software design, the problem is simplified. The subsystem budgeting becomes a tradeoff between sensor performance and mechanism accommodation tolerances. Obviously, if a mechanism can accommodate offsets of several inches or degrees, the sensor requirements need not be in tenths of inches or arc-seconds, for example.

At completion of the subsystem requirements development, the data base of candidates was screened. Candidates passing this initial gate were ranked against criteria developed from study guidelines and for their flexibility in performing additional roles as requirements change. This ranking of candidates and the selection of an autonomous, a manual, and a hybrid system comprised Task B.

Definition of the development test program for each candidate system constituted Task C. A risk analysis was conducted, fidelity requirements were established, and test descriptions, schedules, and procedures were prepared. The MSFC facilities were assessed for applicability to each test and a preferred facility was selected. Necessary modifications to the facilities were identified and test cost developed.

A programmatic costing support activity (Task D) was performed in parallel with the other tasks. This task provided the cost/risk analyses required to support decision-making, particularly in Tasks B and C.

During this study, it became clear that some form of continuing rendezvous and docking system integration activity is required. The recent emphasis on space station and manned tug for future space missions places new system-level requirements on a rendezvous and docking system. The varying emphasis on servicing versus retrieval roles indicates that keeping the options open and providing flexibility in the system will be a prime driver requirement.

V. BASIC DATA AND SIGNIFICANT RESULTS

The complete results of this study are reported in subsequent volumes of this report. Volume II is a complete summary of study results. Volume III presents supporting research and technology and simulation/demonstration plans and procedures. Volume IV reports on supplemental studies in the areas of simulation program development, subsystem requirements derivation, and operations and sensor analyses. Volume V summarizes programmatics analyses. The following paragraphs present an executive summary of these activities.

This study has shown that remote rendezvous and docking can be achieved without new technology. A manual rendezvous and docking system using proven concepts and currently planned developments can be implemented at an approximate development cost of \$11.98M. This approach uses an RF rendezvous radar evolved from the Apollo/lunar module system whose development is planned for the Shuttle orbiter vehicle. It employs a silicon vidicon camera to supply the mission control console operator with the data required to complete docking. The McDonnell Douglas square-frame concept is the recommended docking mechanism for spacecraft retrieval missions. This straightforward approach can successfully achieve the remote rendezvous and docking objective at a low cost, although more advanced approaches appear more desirable.

An autonomous docking objective can be met with some modest new development and at an acceptable development risk. Development cost of the preferred approach is \$17.1M using the GaAs SLR development sponsored by MSFC as the sole sensor in an autonomous mechanization. An alternative approach is to develop the computer algorithms required to automate the interpretation of range and attitude data from TV imagery. While these are not flight-demonstrated approaches, enough development work has been done to assure their viability.

The most reasonable approach to remote rendezvous and docking is a hybrid of the manual and autonomous systems, the recommended system using both the GaAs SLR and a TV sensor. The development cost of this approach is \$18.6M. This approach provides built-in redundant sensing, growth to the autonomous system, the capability of handling routine situations autonomously, and the possibility of bringing man's decision-making capabilities into play for anomalous situations.

Fiscal funding requirements for the rendezvous and docking system options are summarized in Table V-1. Development cost includes SRT and simulation/demonstration testing, as well as Phase B/C definition, design, and development activity. This DDT&E activity will be spread from FY '77 through initial operational capability in 1984 as shown in the table. The DDT&E cost plus first article build cost comprises the total development cost shown in the table and quoted in the previous paragraphs.

Table V-1 Total System Development Cost

SYSTEM	COSTS IN $K						
	DDT&E					First Article	Total Development
	FY 77-78	FY 79	FY 80	FY 81	FY 82-83		
Manual	1700	3674	4292	616	218	1480	11,980
Autonomous	3300	3464	6533	2470	143	1190	17,100
Hybrid	3000	3915	7361	2706	218	1400	18,600

Two new technology areas that offer attractive alternatives appear worthy of further attention. The first is the RF docking sensor. An array of passive time-delay RF retroreflectors on the spacecraft will allow all range and attitude measurements required to effect the docking maneuver to be achieved. This approach is a modest advance of existing RF technology that should be compared with the laser technology more thoroughly than has been possible to date. The other technology adaptation worthy of consideration is nonimpact docking which could be effected via a stationkeeping control mode in the vicinity of the target spacecraft's docking device. This approach offers the possibility of less effect on the spacecraft design (for retrievability) and increased compatibility with servicing missions. The suggested design approach employs a steerable STEM device for docking contact, but could be adapted to the use of proposed servicing devices.

Finally, the role of rendezvous and docking in future space operations is expanding. Several elements of the STS will be engaged in such activities--with a wide variety of spacecraft, both manned and unmanned. Many emerging applications can benefit from the technologies surveyed in this study. A rendezvous

and docking integration activity with a broad charter can enhance the cost effective achievement of rendezvous and docking objectives in future space operations. The creation of such an integration role is recommended.

A. DATA BASE

The categories of data developed or compiled in this study include (1) tug characteristics and performance, (2) selected representative payloads, (3) flight mechanics trajectory analysis, (4) docking dynamics analysis, (5) system requirements, (6) subsystem requirements, and (7) subsystem candidate hardware.

1. Tug Characteristics and Performance - The basic tug system and subsystem configurations and capabilities were defined at the start of the study. The vehicle description was from MSFC's *Baseline Space Tug Configuration Description*, 68M00039-2, dated July 15, 1974. The avionics baseline was defined as a later study output, *Space Tug Avionics Definition Study*, under contract NAS8-31010.

2. Selected Representative Payloads - To evaluate docking techniques, sensors, and mechanisms, realistic spacecraft and mission characteristics were essential. Since hundreds of missions in which docking with spacecraft is desirable for either servicing or retrieving are planned for the time frame under consideration, a smaller representative set of spacecraft was selected to investigate the effect of spacecraft and mission parameters on the docking portion of the mission.

The spacecraft selection process was based on the July 1974 SSPD to determine the automated spacecraft to be flown during the space tug era. These included both those expected to be on orbit and those to be launched during the 1984-1990 time frame. Reference was also made to the payload servicing study (NAS8-30820) and the payload utilization of tug (PUT) study results for payload information and characteristics.

The following criteria were used to select the representative spacecraft:

1) Mission orbit - altitude, inclination, daylight and darkness frequencies;
2) Spacecraft configuration - mass, physical dimensions, and types of appendages;
3) Spacecraft stability - spin- or three-axis-stabilized, deadbands, nominal rates;
4) Other factors - design status, quantities of spacecraft anticipated.

The selection process identified the four representative spacecraft shown in Figure V-1.

The CN-52 and EO-09 represent geostationary altitude payloads and commonality with payloads studied in the PUT study as well as both spin- and three-axis-stabilized spacecraft. CN-52 also represents the lighter end of the anticipated mass spectrum. EO-09 also represents a long satellite.

EO-56 was selected to represent a low earth orbit and a heavy spacecraft. An AP-05, with a medium orbital altitude of 12,780 km (6,900 nautical miles), was selected as the fourth reference spacecraft.

3. Flight Mechanics Trajectory Analysis - A Martin Marietta rendezvous computer program was used to evaluate performance and to determine the system and subsystem requirements for the rendezvous phase [from sensor acquisition at 23 - 46 km (12.5 - 25 n. miles) to stationkeeping at ≈ 90 m (300 feet)]. The program uses a proportional navigation algorithm and simulates the closure of two vehicles in three-dimensional space. A range rate command generated as a parabolic function of range is controlled within a specifiable deadband. Line-of-sight (LOS) rates are nulled within a specifiable threshold. The simulation generates a complete description of the closure maneuver, including propellant usage schedules. The program includes elementary models of sensor measurement errors. The proportional navigation algorithm is suitable for rendezvous closure but not for inspection and docking maneuvers.

Feasibility of the proportional navigation rendezvous algorithm was verified during the study. The following conclusions and specifications were derived from the analysis:

1) Initial ranging sensor acquisition -46 km (25 nautical miles);
2) Rendezvous accomplished in 2 to 3 hours;
3) Energy expended - 6 to 9 m/s (20 to 30 fps);
4) Sensor accuracies not driven by rendezvous requirements.

4. Docking Dynamics Analysis - A terminal docking analysis was performed to aid in determining the docking mechanism requirements for stiffness, damping, interfaces, forces and torques, and postlatch control requirements. This was

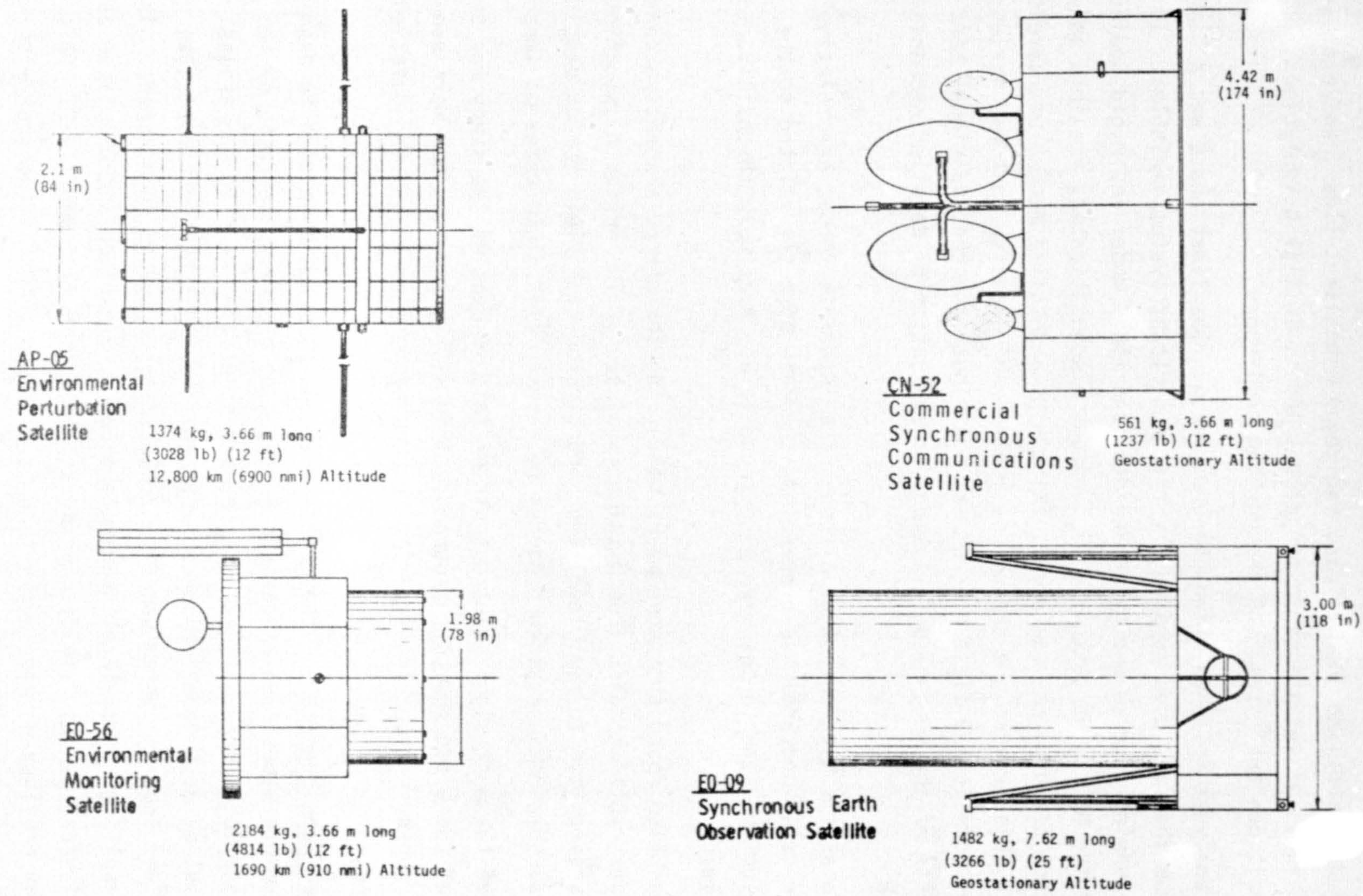


Figure V-1 Four Representative Spacecraft

accomplished by modeling the vehicle, including propellant slosh, and evaluating the effects of variations in propellant level, initial orientations, vehicle attitudes and rates, and the docking trajectory.

The analysis followed a two-phase approach. The first phase was a simplified program that was used to identify the significant system variables. It is a fast-running program employing an idealized fluid model and rigid bodies. In Phase 2 the Martin Marietta IMPRES program, a sophisticated, flexible body dynamics computer program, was used. It permits a detailed mechanism representation. In this program the energy dissipation and transfer that was derived in a lumped form in the first program was distributed to the individual hardware elements of the mechanism, allowing for evaluation of detailed mechanism performance.

The analysis disclosed that although the interface forces are relatively insensitive to spacecraft mass properties, they are directly related to the closing velocity. The forces were also found to be relatively insensitive to tank fill level.

It was also found that some means of varying the energy absorption capability is desirable at least from mission to mission. The energy dissipation required is sensitive to fill level and impact velocity. Fluid motion damping is also desirable because slosh produces relatively high fluid rates at impact.

One of the most significant outputs of this segment of the study was development of these two analysis programs. They will prove more and more useful as the subject of docking dynamics is pursued more deeply in the detailed design phase.

5. <u>System Requirements</u> - A thorough system analysis was conducted to examine the requirements imposed on rendezvous and docking by the spacecraft, by the tug, by other interfaces such as Shuttle, and finally by mission operations. The potential of accommodating spacecraft servicing in a retrieval-oriented rendezvous and docking system was also evaluated as a system requirement. The numerous resulting system-level requirements were summarized and tabulated as shown in Figure V-2, and developed in detail in Volume II, page II-12. This presentation provides a detailed listing of all requirements, together with traceability to their sources.

DERIVED SYSTEMS REQUIREMENTS SUMMARY (continu

SOURCE REQUIREMENT	DERIV
The Space Tug and S/C Shall be Compatible with All Shuttle Imposed Environment	The R/D Systen Orbiter, Tug ar Docking Loads,

DERIVED SYSTEMS REQUIREMENTS SUMMARY (continued)

SOURCE REQUIREMENT	DERIVED REQUIREMENT
Safety Critical Data - The Tug Shall Provide Tug / S/C Safety Critical Data During Deployment / Retrieval by Orbiter	The Rendezvous / Docking System Shall Interfere With Tug / S/C Service Interf (Implies Monitoring and Control Inter

DERIVED SYSTEMS REQUIREMENTS SUMMARY (continued)

SOURCE REQUIREMENT	DERIVED REQUIREMENT	
The Tug Shall be Compatible with SGLS or STDN / TDRSS	The Rendezvous / Docking System Shall be Compatible with the Tug Communications System (e.g. -TM, TV)	IB. Stu TGI
The S/C Shall Provide Redline Limits for Mission Rules, Jettison, Hazardous Fluids, Pressurant Dump and System Safing for	The R/D System Shall Enhance Abort Capability, or as a Minimum Shall Not Preclude Abort ∴ UNDOCKING IS A REQUIREMENT	T M. Par.

DERIVED SYSTEMS REQUIREMENTS SUMMARY

SOURCE REQUIREMENT	DERIVED REQUIREMENT	PRIMARY SOURCE
The Tug Will be Active Element In Providing the Following Services to Passive Spacecraft In the Mission Model: • Retrieval and Retrun to Earth • Servicing	The Rendezvous / Docking System Shall Accommodate Variations in Spacecraft Weights, e.g. and Size Variations for Delivery of One Spacecraft or Set and Retrieval of Another S/C or Set The Rendezvous / Docking System Shall Not Interfere With Servicing of Spacecraft	Tug Rqmt's MSFC 68M00093-1 and RFP
The Tug Injection Accuracies Shall be Known Within: • Position - 4.2 n mi • Velocity - 11.3 fps	The Rendezvous / Docking System Shall be Designed to Accommodate These Variations	Tug Rqmt's MSFC 68M00093-1 Para 3.2.1.2.2.5
The Tug Shall be Capable of Docking With Spacecraft	Docking Misalignments Shall be Removed by the Docking System	GDC Avionics Study
Provisions Shall be Made to Preclude Tug Tank Implosion During Return	Implies Safing Provisions for S/C Shall Also be Provid-- and Reinforces Umbilical R--nnection	IBM Operations Study (Reference TS-24-1-
The S-	--ing Syst-	GDC

Figure V-2 Derived Systems Requirements Summary

The key system requirements are as follows. The spacecraft imposed requirements relate to their range of physical size (Ref. Figure V-1), their attitude stabilization (3-axis and spin stabilized), and their passive cooperative state. The passive cooperative state has been evolved to mean: The spacecraft state vector is known with high accuracy before launch of Tug [1.85 km (1 nautical mile), 0.3 mps (1 fps)]; they will be provided with a docking port/device; and they will provide passive docking sensor targets. The rendezvous and docking system must be able to function within the operational environment imposed by the Tug vehicle, as defined by MSFC's baseline documentation, as modified by GDC's baseline avionics study (except for specifically rendezvous

and docking components). This definition includes baseline navigation accuracy, attitude limit cycle characteristics, maneuver limits, RCS plume characteristics, and propellant slosh configuration. The most significant interface requirements derive from the Shuttle flight loading environment, and Shuttle/Tug, Tug/Spacecraft safety constraints. The principal flight operations imposed requirements divide into functional and mission model derived requirements. Functional considerations require:Inspection of the target spacecraft on site to establish docking readiness; An ability to align with the docking port, to close, and to secure the spacecraft to the tug; Retrieval of the target spacecraft via Shuttle to the ground. The principal model derived requirements are to provide compatibility with delivery of up to three spacecraft and retrieval of one on the same flight, and to provide compatibility with delivering a different diameter spacecraft than the one retrieved. These and other less prominent system level requirements provide the basic framework against which detailed subsystem requirements were derived.

6. Subsystem Requirements - A two-phase approach was used to derive subsystem requirements, i.e., specifications of docking mechanism and sensor hardware performance, and design characteristics. Initially, an error analysis defined the geometric conditions at docking for the various configurations--impact docking, nonimpact docking, etc. Equations were then written using a RSS sumation of errors relating sensor and tug errors to docking mechanism design characteristics. The relationships were parameterized by plotting each of the many variables over anticipated ranges. This determined sensitivity to the variable and permitted a selection of the optimum or least-impact requirements. The second step was to verify these selected requirements with a dynamic docking simulation program (DOCK) developed in the study. It was a fast-running program allowing for Monte Carlo error analyses. A comparison of results for several parameters is illustrated in Table V-2.

Table V-2 Autonomous Configuration Error Analysis Results

Docking Mechanism Design Parameter	RSS Error Analysis		Dynamic Simulation (Program DOCK) Results
	Results	Spec	
Angular Misalignment	.05 rad (3.0 deg)	.08 rad (4.5 deg)	.05 rad (3.0 deg)
Lateral Misalignment	.05 m (.16 ft)	.10 m (.32 ft)	.03 m (.10 ft)

MAN AND/OR CONTROL SYSTEM REQUIREMENTS

REQUIREMENTS	MANUAL	
	IMPACT	NON-IMPACT
a) ACS Minimum Impulse Bit	20 ms	20 ms
b) Lateral Translation Time Capability	.03 m/sec (.1 ft/sec)	.02 m/ (.1 ft

CUE REQUIREMENTS

REQUIREMENTS	MANUAL		AU
	IMPACT	NON-IMPACT	IMPACT
Visual	Offset "T"	Offset "T"	Offset "T", where TV i required

DOCKING MECHANISM REQUIREMENTS

REQUIREMENTS	MANUAL		AUTONOMOU	
	IMPACT	NON-IMPACT	IMPACT	NON-IMP
a) Angular Misalignment	± .08 rad (± 4.5 deg)	± .07 rad (± 4.1 deg) SLR ± .09 rad (± 5.0 deg) RF	± .05 rad (± 2.8 deg)	± .04 rad (± 2.4 deg)
b) Max Lateral Displacement (prior to STEM Contact	± .13 m (± .42 ft)	± .12 m (± .4 ft)	± .1 m (± .32 ft)	± .06 m (± .2 ft)
			.035 m/s .11 ft/sec)	0
			± .03 m/s ± .1 ft/sec)	.005 m (.016 ft
			.09 rad 5.0 deg)	± .09 rad (± 5.0 deg)
			A	± .04 rad (+ 2.4 deg)
				2.5 cm
				.17 r 10 d
				5 ra deg/ 5 m ft)
				minutes
				minute

VIDEO/LIGHTING REQUIREMENTS

CAMERA	
Type	2.5 cm.(1") Silicon Intensified Target (SIT) Tube
FOV	.35 radian (20 degrees)
Resolution	525 Lines x 430 Pixels, Minimum

RANGING SENSOR REQUIREMENTS

REQUIREMENTS	MANUAL		AUTONOMOUS	
	IMPACT	NON-IMPACT	IMPACT	NON-IMPACT
a) Attitude Determination Capability	No	No	Yes	Yes
1) Attitude Determination Maximum Range	N/A	N/A	91m (300 ft)	91m (300 ft)
2) Attitude Determination Minimum Range	N/A	N/A	3m (10 ft)	.9m (3 ft)
3) Attitude Determination Accuracy	N/A	N/A	± 17 mrad (± 1 deg)	± 17 mrad (± 1 deg)
b) Acquisition Range	46 km (25 n mi)	46 km (25 n mi)	46 km (± 25 n mi)	46 km (± 25 n mi)
c) Range Data Minimum	3m (10 ft)	.3m (1 ft)	3m (10 ft)	.9m (3 ft)
d) Range Accuracy - Far - .93 km to 93 km (.5 n mi to 50 n mi)	± 30.5m (± 100 ft)	± 30.5m (± 100 ft)	± 30.5m (± 100 ft)	± 30.5m (± 100 ft)
Near-3m to .93 km (10 ft to .5 n mi)	± .3m (± 1 ft)	±.15m (± .5 ft)(long term) ±.02m (±.08 ft)(short term)	± .3m (± 1 ft)	± .3m (± 1 ft)
Near .9m		N/A	N	±.15m (±.5 ft)(ay) .03m (±.1

Figure V-3 Subsystem Hardware Requirements Summary

The results of the complete subsystem requirements derivations are summarized in the categories illustrated in Figure V-3. More detail is available in Volume II, page II-22.

7. <u>Subsystem Candidate Hardware List</u> - An important part of the data base was the compilation of available or potentially available sensor and mechansim candidates and their detailed performance capabilities, physical properties, and

costs. These candidates form the basis for configuration of the autonomous, manual, and hybrid systems that are basic outputs of this study. Initially many potential candidates were identified in all categories. These were screened using system-level requirements and selectively trimmed to the final list of hardware components shown in Table V-3. The rationale for selecting these candidates is also provided. Detailed characteristics, including costs for each, are presented in subsequent volumes of this report.

Table V-3 Subsystem Final Hardware Candidates

Subsystem	Candidate	Rationale
Sensors		
Laser Radars	• Ga As	• Current Tug Baseline
	• CO_2 Cooperative	• Long Range Capability
	• CO_2 Non-Cooperative	• Minimize S/C Cues
TV	• Silicon Vidicon	• Shuttle Development
RF Radars	• Modified Apollo Rendezvous - Non-Cooperative	• Flight Proven, Minimum S/C Impact
	• Modified Apollo Rendezvous - Cooperative	• Lower Weight And Power
	• Dual Mode - Non-Cooperative (Rendezvous Radar Above Plus Short Range Pulse System)	• Single Unit, Full Range Capability, Minimized S/C Impact
	• Dual Mode - Cooperative	• Lower Power And Weight Than Above
Docking Mechanism		
Impact	• MDAC Square Frame	• Current Tug Baseline
	• MMSE Adaptation From Apollo	• Low Cost And Risk
Non-Impact	• New MMC Design	• Good Servicing Capability, Simpler Structure

B. SYSTEM SELECTION

The approach followed in configuring and selecting the optimum autonomous, manual, and hybrid rendezvous and docking system concepts for this study is depicted in Figure V-4.

The data, such as requirements and candidate hardware (top of Fig. V-4), necessary to arrive at detailed configurations were previously discussed in Section A. Using this data base, possible combinations of sensors and docking

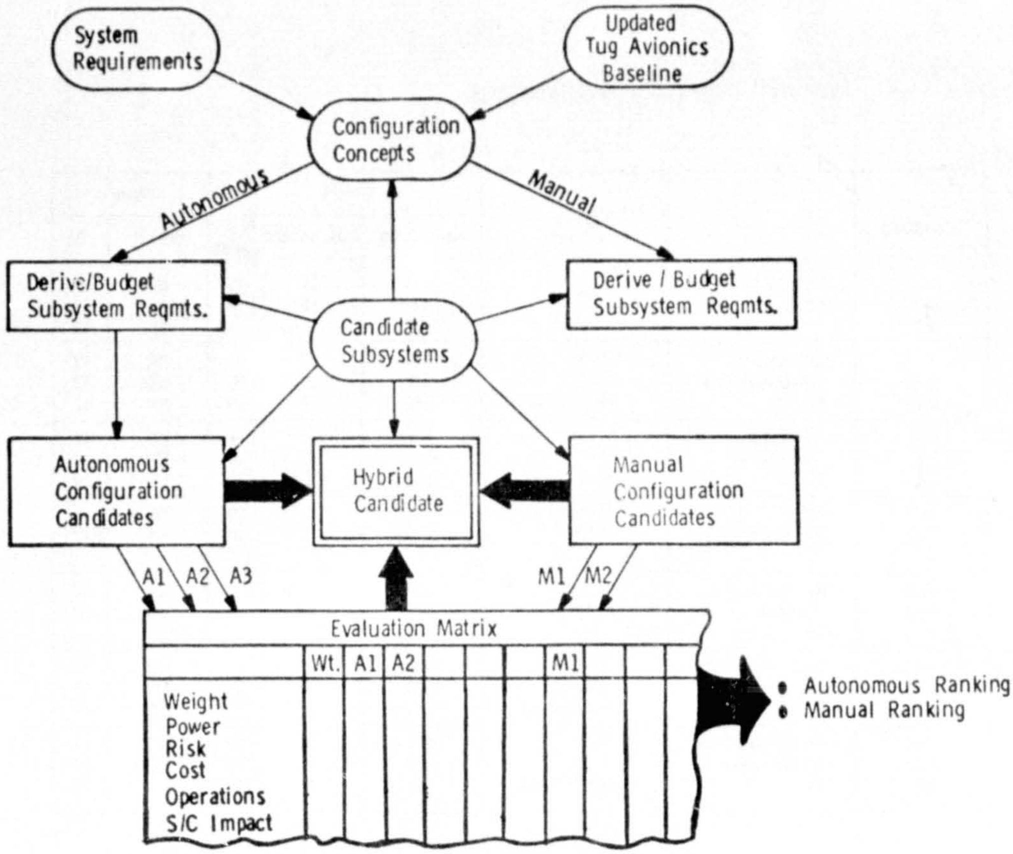


Figure V-4 System Configuration and Selection Approach

mechanisms that met the established system and subsystem requirements were defined. Nineteen candidate combinations were defined for the manual systems and twenty-four for the autonomous system. These candidates, their sensors, and some physical characteristics are summarized in Tables V-4 and V-5.

Note that the hybrid candidate was selected, as shown in Figure V-4, by combining the best features of the autonomous and manual candidates. The criteria for its selection is discussed later.

The autonomous and manual candidates were ranked by evaluating each candidate against a comprehensive set of criteria. These criteria, weighting factors assigned to each, and a summary of the rationale for the weighting factors is provided in Table V-6. The weighting values shown are for the manual configuration. The autonomous configuration is much the same except the development risk and nonrecurring cost were emphasized (3 instead of 2) because of the

Table V-4 Manual Candidate Summary

Candidate	Sensor	Docking Mechanism	Weight			Power	
			Mechanism	R&R Sensor	TV / Lights	Sensor	TV
M1	GaAs SLR	MDAC	556	55	20	40	12
M2	TV	MMSE	970	55	20	40	12
M3		Non-Impact	531	55	20	40	12
M4	CO_2 Laser	MDAC	556	50	20	200	12
M5	(Noncooperative)	MMSE	970	50	20	200	12
M6	TV	Non-Impact	531	50	20	200	12
M7	CO_2 Laser	MDAC	556	40	20	< 100	12
M8	(Cooperative)	MMSE	970	40	20	< 100	12
M9	TV	Non-Impact	531	40	20	< 100	12
M10	Rend. Radar	MDAC	556	75	20	275	12
M11	(Noncooperative)	MMSE	970	75	20	275	12
	TV						
M12	Rend. Radar	MDAC	556	70	20	120	12
M13	(Cooperative)	MMSE	970	70	20	120	12
	TV						
M14	Dual Mode Radar	MDAC	556	80	20	275	12
M15	(Noncooperative)	MMSE	970	80	20	275	12
M16	TV	Non-Impact	531	80	20	275	12
M17	Dual Mode Radar	MDAC	556	75	20	120	12
M18	(Cooperative)	MMSE	970	75	20	120	12
M19	TV	Non-Impact	531	75	20	120	12

Table V-5 Autonomous Candidate Summary

Candidate	Sensor	Docking Mechanism	Weight			Power	
			Mechanism	R&R Sensor	TV / Lights	Sensor	TV
A1	GaAs SLR	MDAC	556	55	-	40	-
A2		MMSE	970	55	-	40	-
A3		Non-Impact	531	55	-	40	-
A4	GaAs SLR	MDAC	556	55	20	40	12
A5	And TV	MMSE	970	55	20	40	12
A6		Non-Impact	531	55	20	40	12
A7	CO_2 Laser	MDAC	556	50	-	200	-
A8	(Noncooperative)	MMSE	970	50	-	200	-
A9		Non-Impact	531	50	-	200	-
A10	CO_2 Laser	MDAC	556	50	20	200	12
A11	(Noncooperative)	MMSE	970	50	20	200	12
A12	And TV	Non-Impact	531	50	20	200	12
A13	Rendezvous Radar	MDAC	556	75	20	275	12
A14	(Noncooperative)	MMSE	970	75	20	275	12
A15	And TV	Non-Impact	531	75	20	275	12
A16	Rendezvous Radar	MDAC	556	70	20	120	12
A17	(Cooperative)	MMSE	970	70	20	120	12
A18	And TV	Non-Impact	531	70	20	120	12
A19	Dual Mode Radar	MDAC	556	80	-	275	-
A20	(Noncooperative)	MMSE	970	80	-	275	-
A21		Non-Impact	531	80	-	275	-
A22	Dual Mode Radar	MDAC	556	75	-	120	-
A23	(Cooperative)	MMSE	970	75	-	120	-
A24		Non-Impact	531	75	-	120	-

Table V-6 Weighting of Evaluation Criteria

	Weight	Rationale
Mechanism Weight	2	Major Differences, But Tug Impact Only
Sensor Weight	1	Small Differences, Tug Impact Only
Power	1	Accomodated Within Tug Design
Development Risk	2	A Major Factor But Long Lead Times Are Planned
Mission Success Probability	2	Long Lead Times Should Enhance This Aspect
Software	2	Presents Risks, But Are Tug Concerns Only
Mission Operations (Complexity)	2	Important For Manual, But Not Major Driver
Servicing Potential	3	Major User Concern
Spinning Spacecraft (Compatibility)	2	Major User Concern But Few Users Identified
Spacecraft Impact-Struct.	3	Major User Concern
Spacecraft Impact-Cues	2	Major User Concern, But Much Lighter
Ground Operations (GSE)	1	No Great Differences From Candidate To Candidate
Recurring Cost	2	Important But No Dramatic Cost Restrictions Anticipated
Nonrecurring Cost	2	Important But No Dramatic Cost Restictions Anticipated

higher technology level anticipated. Mission operations complexity was reduced from 2 to 1 because of the reduced ground participation in the autonomous configuration. How these criteria were used in ranking the candidates is illustrated in the example in Figure V-5 for the manual configuration.

A rating value was assigned by comparing, or ranking, the candidates with each other considering only one criterion at a time. The objective was to judge fairly and quantitatively a large number of complex systems by examining their characteristics individually. The ratings arrived at were then multiplied by the weighting factor to establish a value. The totals of these values formed the basis for comparison of the candidates.

For the manual configuration, the top three ranking candidates are shown in Figure V-6 with selection rationale. The highest ranked and the optimum manual candidate is comprised of an RF radar for rendezvous [down to ≈ 30 m (100 ft)] and downlink TV to a man on the ground to control the vehicles from 30 m until docking is completed. It is an impact docking approach employing the

Evaluation Criteria	Weight	M1		M2		M3		M4		M5		M6	
		CANDIDATE											
		R	V	R	V	R	V	R	V	R	V	R	V
Mechanism Weight	2	4	8	1	2	4	8	4	8	1	2	4	8
Sensor Weight	1	4	4	4	4	4	4	4	4	4	4	4	4
Power	1	5	5	5	5	5	5	1	1	1	1	1	1
Development Risk	2	3	6	3	6	3	6	1	2	1	2	1	
Mission Success Probability	2	4	8	4	8	5	10	5	10	5	10	5	
Software	2	4	8	4	8	3	6	4	8	4	8		
Mission Operations (Complex.)	2	3	6	3	6	2	4	3	6	3	6		
Servicing Potential	3	3	9	2	6	5	15	3	9	2	6		
Spinning Spacecraft Compat.	2	4	8	4	8	2	4	4	8	4	8		
Spacecraft Impact-Struct.	3	3	9	3	9	4	12	3	9	3	9		
Spacecraft Impact-Cues	2	4	8	4	8	4	8	5	10	5	10		
Ground Operations (GSE)	1	3	3	2	2	3	3	3	3	2	2		
Recurring Cost	2	3	6	2	4	3	6	2	4	1			
Nonrecurring Cost	2	3	6	4	8	2	4	1	2	1			
TOTAL		95		84		95		84					
Docking Mechanism		MDAC		MMSE		Non-Impact		MDAC					
Sensor Group		SLR (Coop.) TV											

NOTES

Weight: 1 - Less Important
3 - More Important

R - Rating, 1 - Poor
5 - Good

V - Value, Weight x Rating

Figure V-5 Candidate Ranking Summarization

Rank (Score)	Sensors	Mechanism	Rationale
1 (103)	RF Rendezvous Radar (Noncooperative) And TV M10	MDAC Square Frame	• Maximizes Manual Participation • Lowest Cost • Lowest Development Risk • No Ranging Cues On S/C
2 (96)	Dual Mode RF Radar (Non-cooperative) And TV M14	Non-Impact System	• Reasonable Recurring Cost • Good Servicing Potential • "Close In" Radar Requires Development • Some S/C Cues Required
3 (95)	GaAs SLR And TV M1	Non-Impact System	• Low Weight & Power • S/C Cues Required • Further Development Required • Good Servicing Potential

Figure V-6 Preferred Manual Candidate Ranking

square-frame docking mechanism. A block diagram of the manual system is shown in Figure V-7. An estimate of the software required in the tug computer is also shown. Note that with the skin tracking (noncooperative) RF radar, only a TV imaging cue is required on the spacecraft.

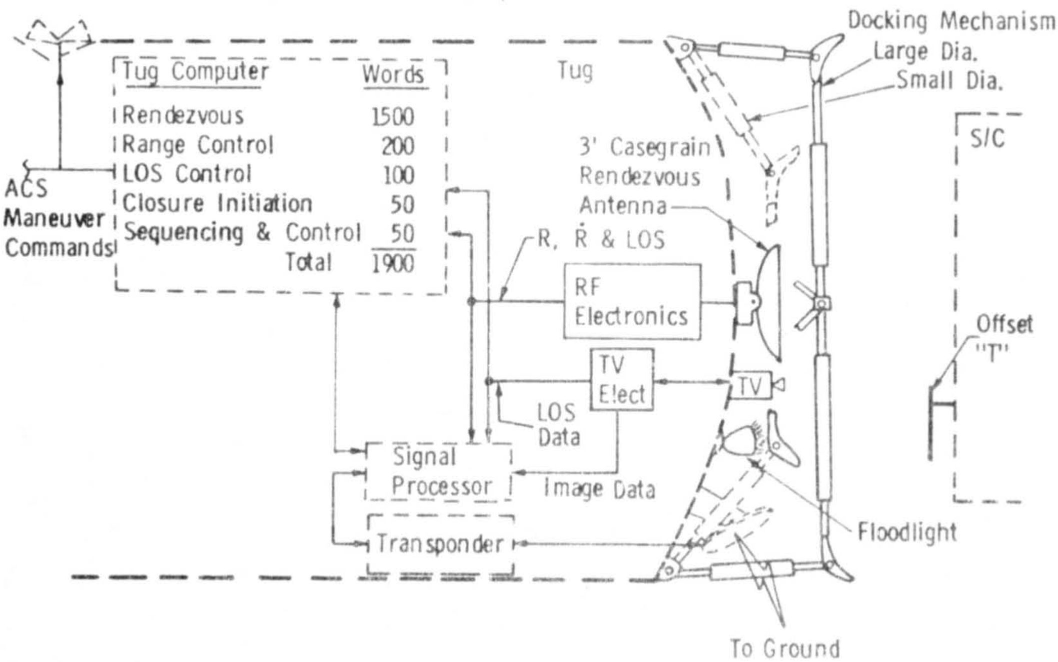


Figure V-7 Manual Candidate Configuration

Mission support will require the mission control computer complex to interface downlinked data with a control center console. The console will display visual data on a screen, and formatted digital data (range, range rate, etc) on a CRT. Hand controls will be provided for manual translation and rotation commands. The downlink data rate is assumed to be the current Tug rate of 50 kbps. With this limitation, it is recommended that some data compression of imaging data be done on board, and an image recreated in the ground computer as one means of improving response time.

The autonomous candidate evaluation was conducted in the same manner as the manual system. The three top ranking candidates are shown in Figure V-8.

Rank (Score)	Sensors	Mechanism	Rationale
1 (94)	GaAs SLR A1	MDAC Square Frame	• Low Weight & Power. • Single Sensor For Range And Target Attitude. • Demonstrated Feasibility
2 (91)	Dual Mode RF Radar (Noncooperative) A19	MDAC Square Frame	• Partially Flight Qualified. • Current Technology
3 (89)	Rendezvous Radar & TV A13	MDAC Square Frame	• Low Cost • Low Hardware Development Risk • Minimum S/C Impact • High TV Algorithm Development Risk

Figure V-8 Autonomous Candidate Ranking

The GaAs scanning laser radar was the sensor selected. It provides all necessary information including target attitude data down to a range of 3 m (10 ft), the minimum required for the impact docking mechanism selected. The other systems require more development either in hardware for the second ranked or in TV imaging processing for candidate 3. The square-frame docking mechanism was selected in all cases due to the higher development risk involved in achieving reliable autonomous nonimpact system performance.

The selected autonomous candidate is depicted in Figure V-9. Note the additional retroreflector on the spacecraft required to ensure the vehicle can be acquired and its orientation determined by sensor tracking alone. Also, the software requirements are larger than in the manual case.

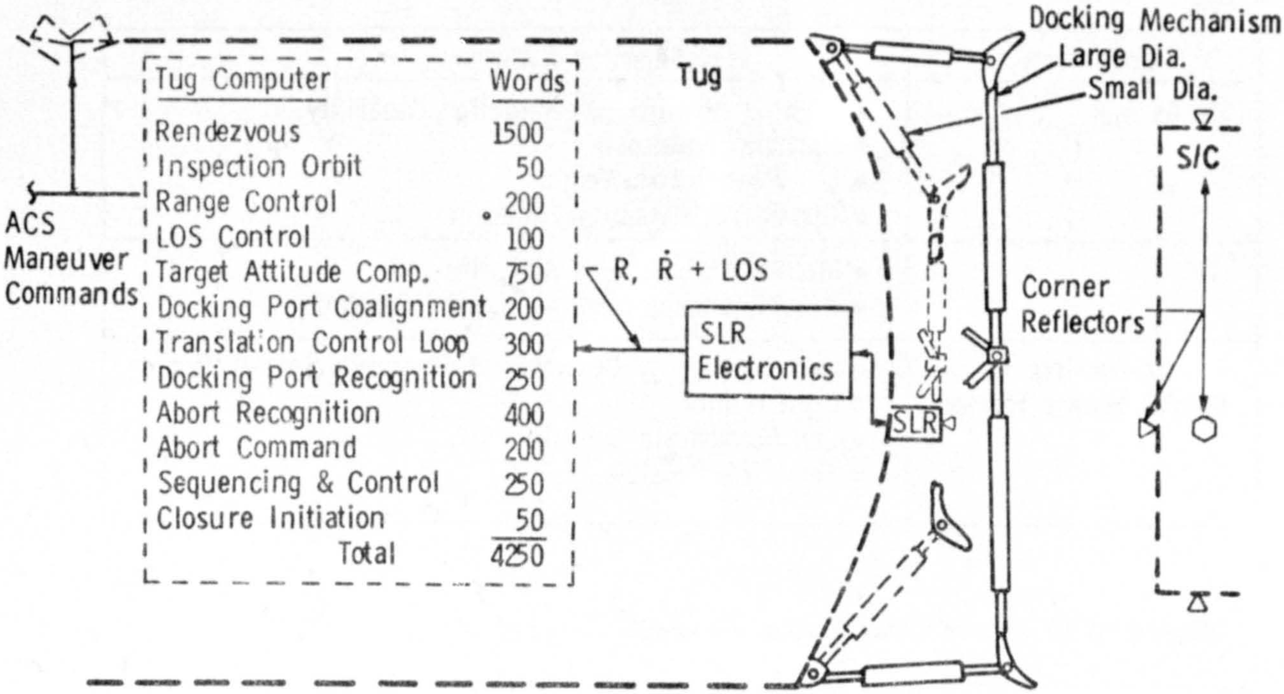


Figure V-9 Autonomous Candidate Configuration

The hybrid configuration, as pointed out earlier, was intentionally limited to a single candidate made up of the best features of both the manual and autonomous configurations. Other qualities that were design objectives for the hybrid were to (1) provide a growth to more autonomy, (2) possess a growth potential for servicing, (3) capitalize on inherent redundancy, (4) relieve critical dependence on the ground, (5) provide a good adaptability to changing requirements, and (6) avoid high-risk autonomous functions such as decision algorithms.

With these criteria a strategy was selected for the hybrid that employed an autonomous means of performing each of the sequences, but utilizing the ground to monitor the activity and at each decision point provides the "go" or "no-go" for the next phase. The resulting hardware components of the hybrid system are summarized in Figure V-10 along with the rationale for their selection. The system is portrayed in block diagram form in Figure V-11. It is felt this hybrid configuration represents the most conservative and logical engineering approach toward development of a versatile, high-capability rendezvous and docking system.

Component	Selection Rationale
Ga As SLR	• Existing Attitude Determination Capability • Partially Developed • Low Power, Low Weight • Considerable Accuracy Margin
TV	• Monitor Autonomous Activities • Provide Backup Manual Docking Capability
Impact Docking (MDAC Square Frame)	• Less Technology Development Than Non-Impact System • Light Weight • Can Accomodate Spinning S/C • Servicing Possible

Figure V-10 Hybrid Candidate Hardware Selection

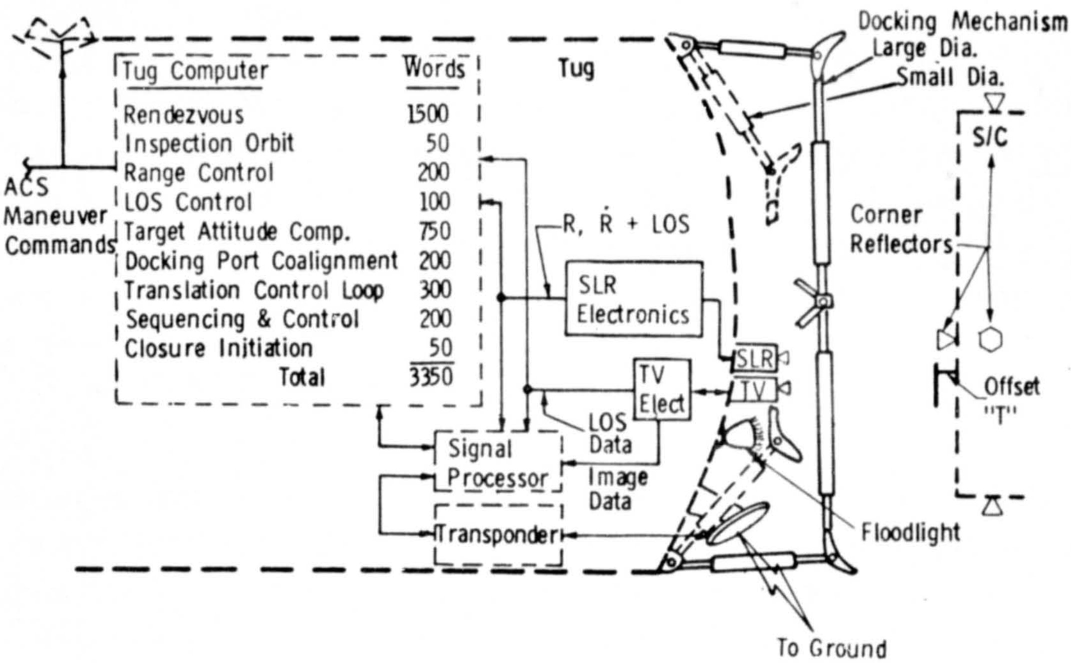


Figure V-11 Hybrid Candidate Configuration

C. SYSTEM DEVELOPMENT PROGRAM

The development program encompassed activities related to new technology or new applications of existing technology. Included were supporting research and technology (SRT), software algorithm development, and simulation/demonstration testing. This program was defined in the manner illustrated in Figure V-12.

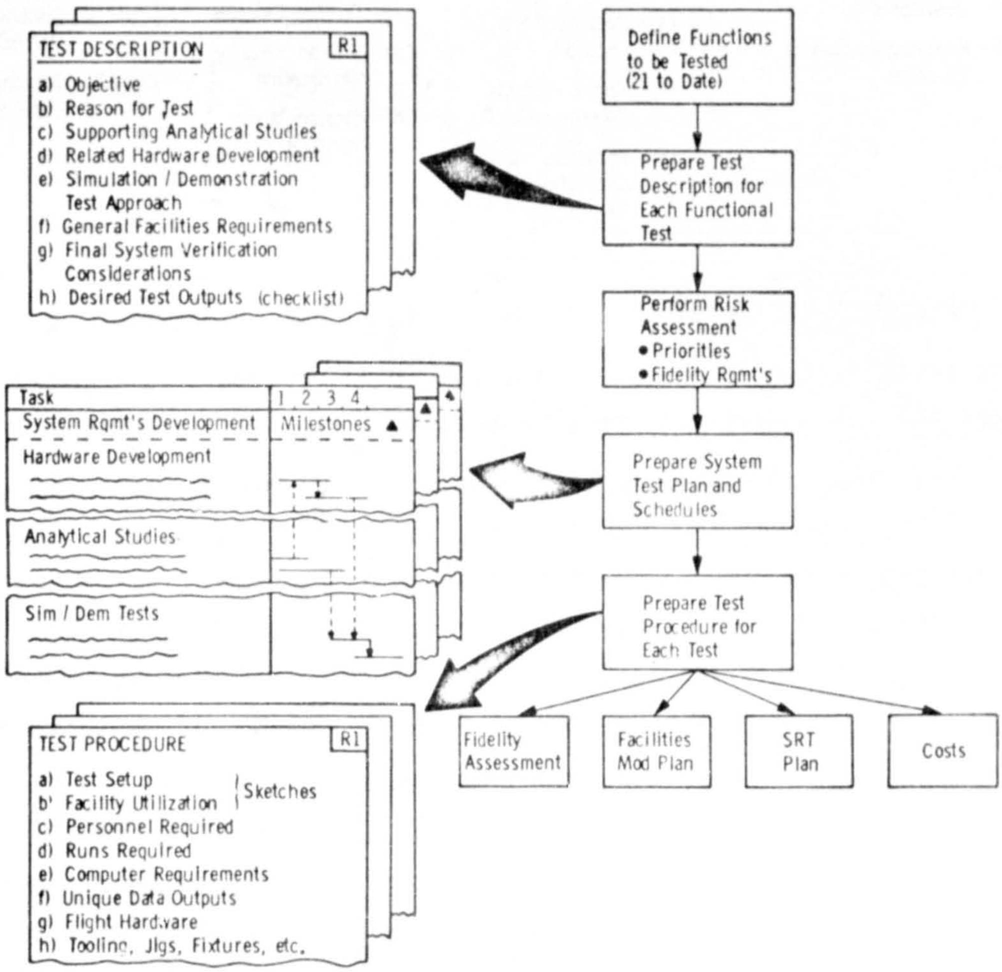


Figure V-12 Approach to Development Program (Task C)

Functions were identified by flight phase, and a technical risk analysis performed. The criticality of each functional test was ranked with the highest priority test being that requiring the most development work. The specific tests surviving this screening process in the rendezvous, inspection, close and dock categories are shown in Figure V-13. This constitutes the recommended simulation/demonstration test program. Test descriptions were prepared for each of

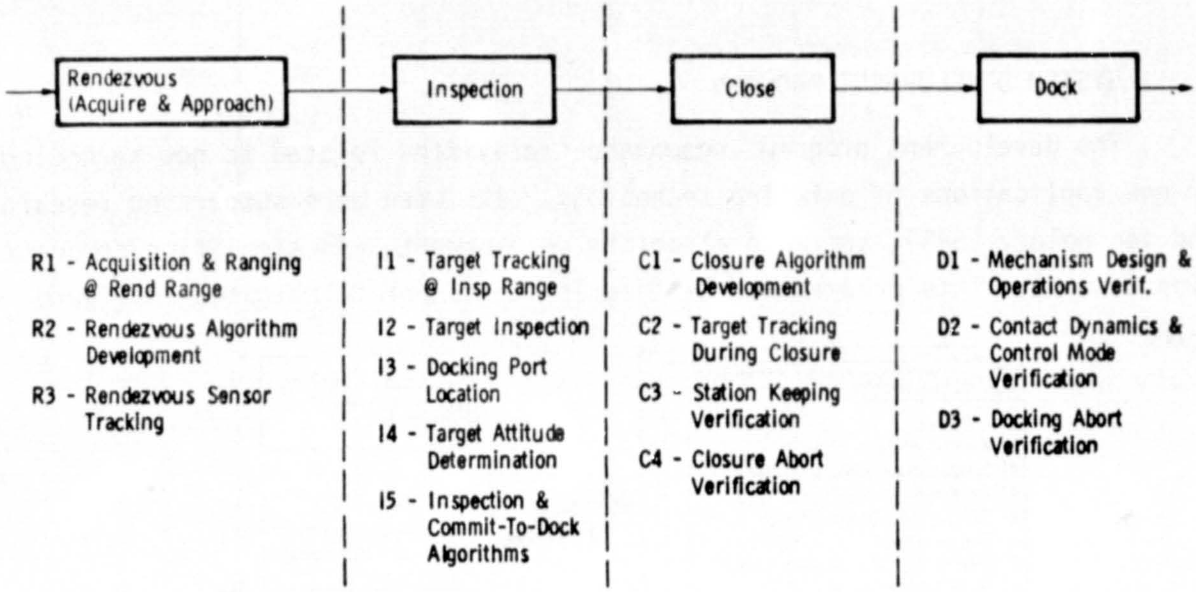


Figure V-13 Selected Simulation/Demonstration Tests

these tests, with separate descriptions being evolved in those cases where the manual and autonomous test requirements were distinctly different.

The fidelity requirements for each test were assessed with regard to tug, spacecraft, lighting, celestial scene, and dynamics fidelity. Concurrently, the existing MSFC simulation facilities were assessed to match the test requirements with the facility capabilities. The match-up that makes maximum use of MSFC facilities is illustrated in Figure V-14. The detailed procedures and plans developed in this study may be found in Volume III of this report.

The parallel development of autonomous and manual rendezvous and docking system capability is recommended, with the best attributes of each system being combined into a hybrid system. This approach is illustrated in the schedule (Fig. V-15). By carrying at least two candidates forward into the simulation/demonstration test program, the options are kept open. One candidate system can be selected for full-scale development (Phase C/D). This approach permits the flexibility to adjust to changing requirements.

As indicated in the overview schedule, some supporting research and technology and algorithm analyses are predecessors to performing the simulation/demonstration testing. Also in the area of commit-to-dock or abort decision

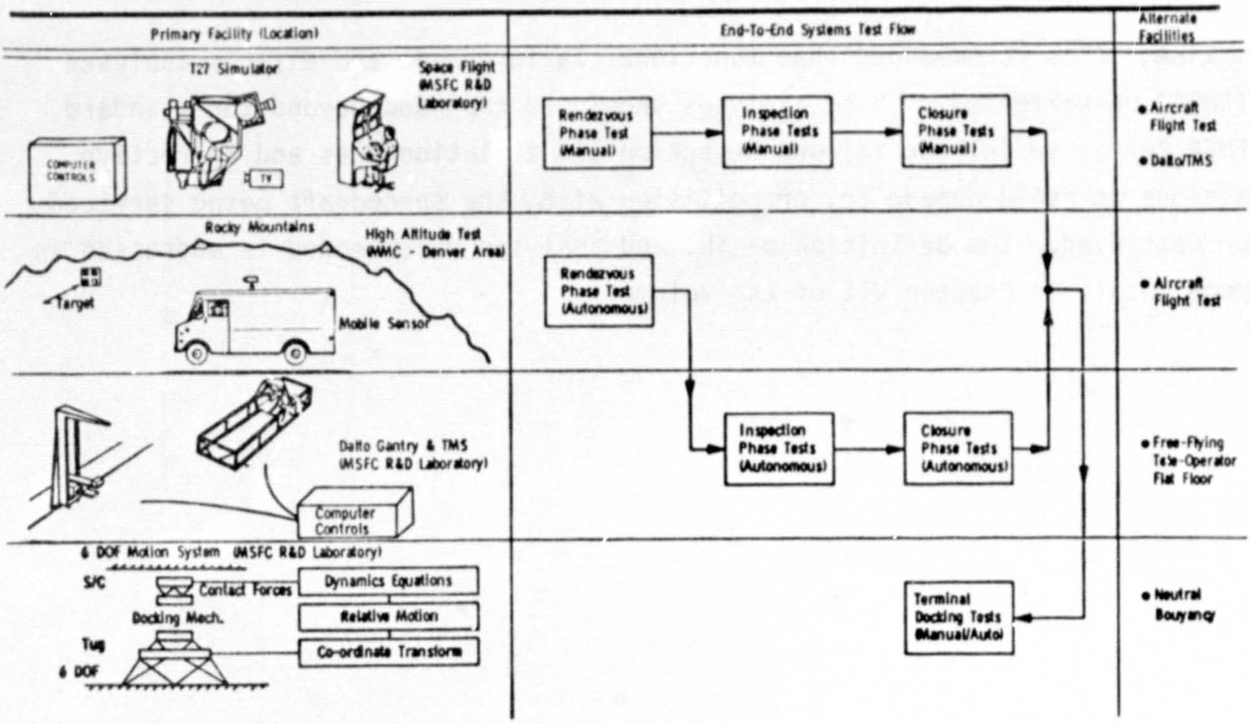


Figure V-14 System Test Flow

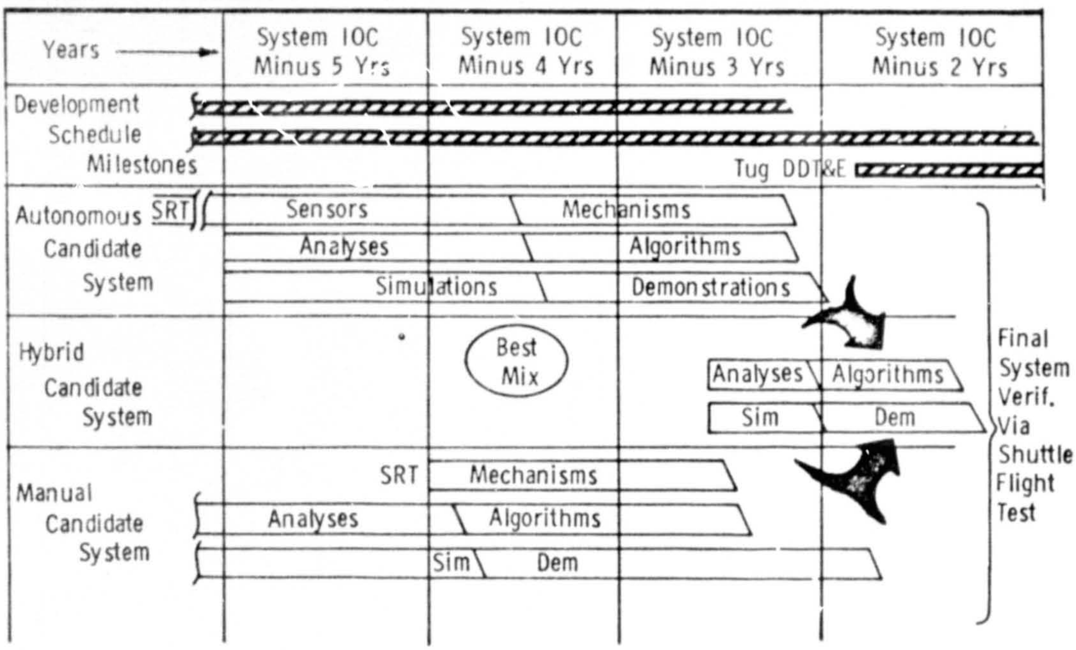


Figure V-15 Recommended Development Test Schedule

making, it is recommended that functional failure mode and effects analyses (FMEA) be performed. These analyses should be expanded beyond the standard FMEA format to include failure detection and isolation cues and corrective actions to avoid damage to, or collision with, the spacecraft being serviced or retrieved. The definition of SRT and analyses recommended is addressed in more detail in Chapter VII of the volume.

VI. STUDY LIMITATIONS

This study has been fruitful and has added a large measure of confidence in the feasibility of, and preferred approaches to, remote rendezvous and docking. Due to time and funding limitations, not all aspects could be explored as thoroughly as must eventually be done. The following study limitations seem most significant.

The performance of systems in which man is an integral part of the control loop is not well-defined. It is not possible to accurately estimate the ability of man to derive the lateral velocity component, for example, using a TV sensor without simulation of the specific system. Some work has been done along this line both at General Dynamics and Martin Marietta, but not with the currently proposed systems. This quantification will be one of the more important advances resulting from the proposed simulation/demonstration testing.

In this study excellent progress was made in setting up tools to analyze the docking dynamics problem although time was not sufficient to exercise these tools to develop a statistical understanding of the capture limits of the recommended docking mechanisms. A significant part of the problem is the relatively large amounts of computer time required to run these simulations. More work specifically oriented toward establishing statistical boundaries should be instituted.

Simulations of all phases of rendezvous and docking were developed and/or exercised during this study, with the exception of the inspection phase. This area is not considered to be of high risk but needs to be addressed later in the form of a digital simulation that will provide an equal level of detail throughout the sequence. The planar docking maneuver simulation developed was adequate to assure feasibility. A complete estimate of docking propellant requirements and probable approach dispersions requires that this simulation be widened to three-dimensional space. A soft-docking stationkeeping simulation should also be added.

The array of activity that should be pursued to complete the pre-Phase B system development is outlined in the next chapter.

VII. IMPLICATIONS FOR RESEARCH

The subsystems ranked highest for autonomous, manual, and hybrid candidates encompass a wide range in development status. In the sensor area, only the TV camera has been used in space. However, a new version of the silicon vidicon camera selected for the Shuttle program is recommended for the rendezvous and docking system from the commonality and shared development cost aspects. The scanning laser radar and RF units are new technology or new applications of existing technology.

In the mechanisms area, the requirements of the study dictated a new design. The existing Apollo and Apollo/Soyuz Test Project designs were required to accommodate a pressurized tunnel for crew transfer. This requirement did not exist for the present study and imposed an excessive weight and complexity penalty under the existing ground rules. These designs also ranked low in servicing compatibility and spacecraft despin capability.

A. COMPONENT SUPPORTING RESEARCH AND TECHNOLOGY

The component SRT for the rendezvous and docking system basically falls into two categories--sensors and mechanisms. Included with the sensors are the electronics for signal conditioning and processing to present a standard interface with the space tug. This approach allows evaluation on a common basis, less impact on tug schedules, and flexibility for using the system on other vehicles or for other applications.

1. Sensors - For the manual candidate, a TV camera was used for docking and an RF radar for rendezvous. This results in minimal component SRT for the sensors *per se*. However, the console operator using the TV image for control must determine range, target attitude, and line-of-sight angles. It is recommended that a microprocessor be used in conjunction with spacecraft-mounted patterns to assist the console operator in these determinations.

For the autonomous candidate the SLR and/or RF radar components present new technology that should be pursued before entering a simulation/demonstration program. Although RF radar is an existing and well-known technology, this application represents a new range of operations not fully proven. In conjunction

with these new developments the target-mounted reflectors or aids represent areas in which research should be performed. Since user acceptance of the system is enhanced by minimizing the impact on spacecraft design, this is a fertile area.

2. Mechanisms - Selected mechanisms for the autonomous, manual, and hybrid systems were much the same. The McDonnell Douglas square-frame design and a nonimpact design are recommended for further SRT development. Both designs represent new technology and require additional development before proceeding into a simulation/demonstration program. The ability to despin a spinning spacecraft is an area in which additional research could be beneficial, and the advantages of a nonimpact system for spacecraft servicing cannot be overlooked. Minimization of the acceleration imparted to the spacecraft being serviced could eliminate the requirement for retracting appendages such as solar arrays and antennae and thus achieve more widespread user acceptance.

B. ALGORITHM DEVELOPMENT

Algorithms or strategies are the methods used to accomplish inspection, alignment, and docking. These strategies divide into decision, maneuver, sensor utilization, and redundancy management categories. The degree of autonomy determines which strategies are performed by man and which must be computerized. Even for the manual system, many functions are automated, e.g., closing the tug control loop around the inertial platform. Figure VII-1 illustrates the relationship of the strategies required to accomplish docking. The computerized strategies may

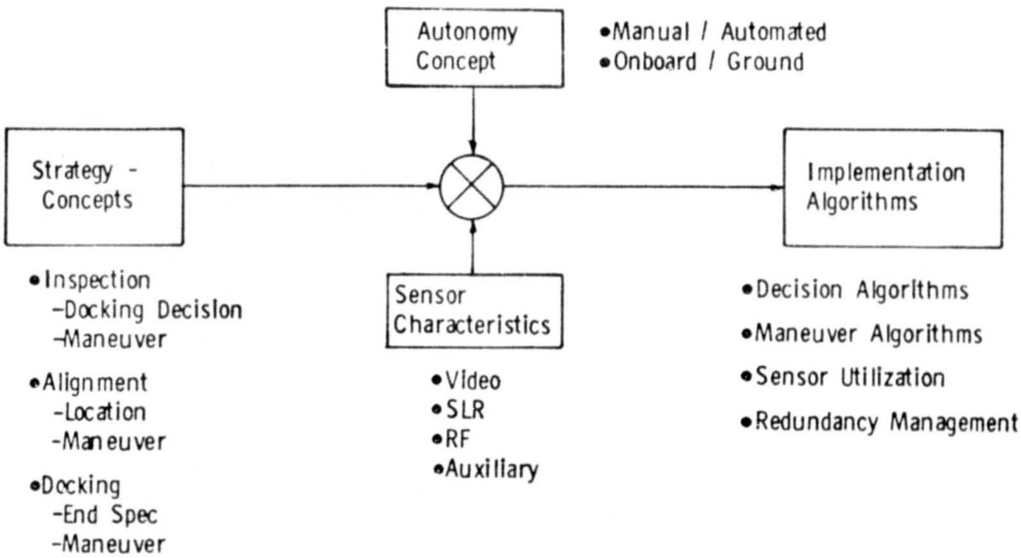


Figure VII-1 Strategies/Algorithms for the Docking Function

be implemented via an onboard computer (space tug or microprocessor) or in ground-based mission control facilities.

For the manual system the data management network can be potentially overloaded by high data rates. This develops a need for image data compression onboard and image reconstruction in the ground-based computer facilities. For the manual system a pattern recognition algorithm to assist the operator in determining spacecraft attitude and docking port location is also an algorithm candidate, as are the algorithms for using the TV image to compute range, LOS angle, target attitude, and their rates.

For the autonomous candidate, all functions must be accomplished by software control. Of particular concern are the decision algorithms for inspection, commit-to-dock, and abort. Rendezvous, inspection, closure, and terminal docking maneuver algorithms must be developed. In all cases, this activity implies the analyses, software requirements generation, coding, and validation. These algorithms should be developed to support the simulation/demonstration test activity during which the software can also be validated.

C. SIMULATION/DEMONSTRATION FACILITY DEVELOPMENT

During the study the existing MSFC simulation facilities were assessed. Their applicability to the rendezvous and docking system and their advantages and disadvantages are tabulated in Table VII-1. Several facility modifications are required to extend current capability to fit rendezvous and docking simulation/demonstration requirements. Some of these are specifically related to manual testing, and some are required for both.

The manual facility modifications are associated with the T-27 Space Flight Simulator. The operational range of the celestial sphere, earth occultation and mission effects projector must be extended to include orbital altitudes from 1670 km (900 nautical miles) to geostationary, and inclinations from 0 to 1.8 radians (105 deg). Software must be added to simulate tug control laws, tug and spacecraft dynamics. In addition, provision of a variable time delay between the T-27 and the remote control console will be required.

Table VII-1 MSFC Facility Assessment

FACILITY	SUITED TO	APPLICATION TO REND & DOCK S/S DEV	CONCERNS
T27 Space Flight Simulator Bldg 4663	• Visual Simulation • Man-in-the-loop • Scaled Down Scenario • 2 Independent Moving Bodies • Lighting Effects/Celestial Scene • Full Circumnavigation	• TV Inspection • TV Closure • TV Rendezvous (Acquisition)	• Fidelity for Camera Evaluation • TV Operational Problem Simulation
Target Motion Simulator Bldg 4663	• Scaled Down System • Man-in-the-loop • Visual Simulation • T27 Provided Celestial Scenes	• Selected TV Operations • SLR Close-in Stationkeeping	• No Target Circumnavigation
Dalto Gantry Bldg 4663	• Terrain Traverse • 3 Axes of Translation Plus Sensor Head Rotation • Full Scale Hardware Possible	• Closure Phase Sensors and Algorithms • Docking Port Locator Cue Evaluation	• Modification Required • 1 Axis of Translation Is Limited
6 DOF Motion Simulator Bldg 4663	• Full Scale Hardware • 6 DOF Dynamic Evaluation	• Docking Mechanism Evaluation (Loads, Latches) • Close-in Sensor Evaluation	• Computer Generated Vehicle Dynamics • Facility Modifications
Teleoperator Flat Floor Bldg 4705	• 5 DOF • Semi Scaled Down Hardware	• Final Closure Concepts • Target Cues Evaluation • Close-in Sensor Evaluation	• Instrumentation • Control System Fidelity
Test Lab Flat Floor Bldg 4711	• Full Scale Hardware • 75' Vehicle Range • 3 DOF Minimum	• Inspection Phase Sensors And Algorithms • Docking Mechanism Evaluation	• Instrumentation • Vehicle Motion Fidelity
Neutral Buoyancy Bldg S4706	• Full Scale Hardware • Close-In Operations	• Docking Mechanism Evaluation • Latch Vehicle Dynamics • Stationkeeping Control-Close-in	• Fluid Damping Effects On Vehicle Dynamics • Sensor Signal Attenuation
Concept Verification Test Facility Bldg 4708	• Space Tug Avionics Development	• Interface Verification • Tug Software • Communications Links	

The autonomous facility modifications are associated with setting up the Dalto gantry to operate in conjunction with the Target Motion Simulator (TMS). The TMS must be physically relocated to permit mounting the rendezvous sensor in alignment with the Dalto gantry track. The gantry camera mount will be used to mount the target mockup--and addition of two axes of rotation to this mount is recommended to allow a more realistic simulation of relative motion. An increase in the traverse translation motion is also recommended, for the same reason. Software support of this facility must be expanded to simulate Tug control and Tug and spacecraft dynamics.

Both manual and autonomous rendezvous testing require the outfitting of a mobile rendezvous sensor test bed, and preparation of full scale mockups of

target vehicles with passive tracking aids. The mobile unit will be based on a small van and will mount the rendezvous sensor and required operating and data gathering support systems.

Docking test facilities involving the 6 DOF motion system are also required for both manual and autonomous systems. The active vehicle portion of the mechanism will be mounted on the 6 DOF motion system. The passive or target spacecraft portion of the mechanism will be suspended from the ceiling of the test area. Instrumentation of the mechanisms to measure dynamic response as well as development of the dynamics and control software for the system is required.

VIII. SUGGESTED ADDITIONAL EFFORT

The future activities recommended as a result of the conclusions reached in this study, and the restrictions on what could be accomplished at this time, are summarized in the PERT/time flow diagram shown in Figure VIII-1. This activity falls into three general areas--supporting research and technology (SRT), simulation/demonstration testing, and rendezvous and docking integration.

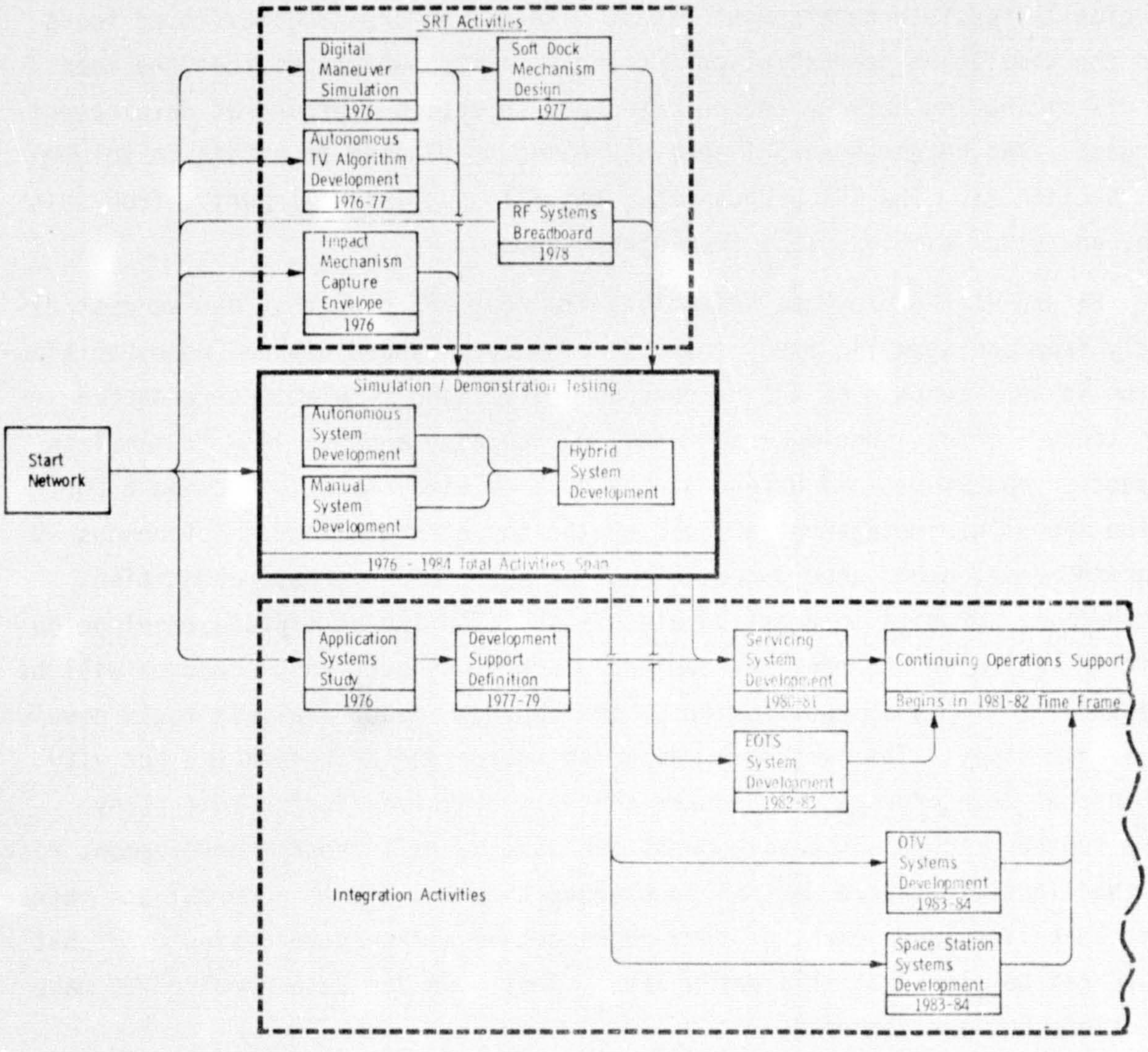


Figure VIII-1 Recommended Future Activities

The simulation/demonstration activity definition has been one of the principal outputs of this study and has been described in detail elsewhere in

this series of reports. Figure VIII-1 therefore simply shows the total span time without a detailed breakout of subsidiary activity. This activity will continue until it merges into the Phase B design of the last rendezvous and docking application--the manned orbital transport vehicle, and the space station it supports.

SRT activity provides the long lead support required to define the technologically feasible development paths. The SRT information developed feeds into the simulation demonstration testing activity, which provides the means for discriminating between technologies and selecting a preferred development approach. The recommended SRT activity has been planned in detail in Volume III, Section II. The SRT program that actually evolves will derive from this plan, and other similar plans from other sources.

Figure VIII-1 presents selections from our SRT plan that derive most directly from our specific study results. The recommended digital maneuver simulation is an outgrowth of the rendezvous and docking simulations conducted in this study. Effort should concentrate on including a capability to simulate inspection maneuvers, and extending the docking simulation to include 6 DOF motion and plume impingement effects on the target spacecraft. Autonomous TV algorithm development should concentrate on inspection/target recognition, measurement, and data compression algorithms. The impact capture envelope definition, defining the range of contact dispersions over which capture will be effected, is simply an application of the docking impact analysis tools developed in this study. The soft dock mechanism design and RF breadboard activity are further developments of hardware concepts conceived during this study. These further technology developments can ease overall program development risk. All these activities are worthwhile because they are either a normal and necessary capability advancement or they represent an alternative design path that should not be closed at this early date. They generate data required to make selections between concepts.

The recommended integration activity (Fig. VIII-1) is defined to assure that *all* STS rendezvous and docking activity is considered in perspective. The development and implementation of this capability must respond to all requirements in an effective manner, not piecemeal as the problems arise. An applica-

tions systems study should be implemented immediately. This effort should be followed by broadly based development activity until support is required for specific applications. Servicing missions--perhaps an IUS application--are likely to be the first rendezvous and docking missions beyond low earth orbit Shuttle operations. The Earth Orbital Teleoperator System (EOTS) is expected to supplement Shuttle capability. These developments precede and lead normally to the high earth orbit capability provided by the Orbital Transport Vehicle (OTV). This system is likely to operate in both manned and unmanned modes. It will provide complete STS services throughout the remainder of this century, particularly supporting the deployment and operation of the geostationary space station. It is important to the operational success of the OTV that a continuous thread of rendezvous and docking development be maintained from the initial shuttle applications onward. It is particularly important that this continuity of effort be initiated now.

Table VIII-1 summarizes the characteristics of the rendezvous and docking applications systems study that should be implemented immediately. This effort

Table VIII-1 Rendezvous and Docking Applications Systems Study

Objective:

Define An Integrated Approach To Rendezvous And Docking System Development And Operations That Meets All STS Objectives

Approach:

- System Requirements Generation
  - Compile Planned & Projected STS Rendezvous & Docking Activity
  - Conduct Functional Operations Analyses
  - Develop Time Phased System Requirements
- Integrated Development Approach
  - Develop Technique/Mechanization Alternatives
  - Define Time Phased Development Paths
  - Select & Define The Most Effective Development Approach
- Integrated Operational Approach
  - Develop Alternative Operational Concepts
  - Select & Define The Most Effective Operational Approach
- System Interface Definitions
  - RDS/STS Vehicles
  - RDS/Retrievable-Servicable Spacecraft
  - RDS/Flight Support Systems

is badly needed at this time to assure the developments already beginning in support of Shuttle objectives are pursued with a view broad enough to permit economical growth toward all STS objectives of the next decade. The proposed study would begin with a broad requirements analysis. Integrated development and operational approaches would then be selected. The final step would involve interface definitions that assure compatibility between the rendezvous and docking system and directly related transportation, spacecraft, and ground support elements. This effort would result in a clear definition of the rendezvous and docking integration role that must be pursued throughout the STS era.

These recommended activities will assure the overall rendezvous and docking objectives associated with the exploitation of space are met completely, effectively, and economically. They should be pursued on a timely basis in the interest of saving total STS program dollars and of increasing total program yield.